Heat-resistant metals, especially boiler heating tubes, become unserviceable more rapidly owing to scale formation [1, 2].

The service life reduction of a metal due to scale formation can be calculated from the kinetic equations of corrosion processes [3] and the equation of long-term strength.

Reduction in the wall thickness of boiler heating tubes, due to corrosion, with constant pressure of the working medium, leads to a continual increase in stress. This can be written [4] in the form

\[ \sigma(t) = \frac{k_p p}{s_0 - \Delta s(t)} \text{[kg/mm}^2\text{]} \]

Here \( p \) is the pressure of the working medium, \( \text{kg/cm}^2 \); \( k_p \) is a coefficient; \( \Delta s(t) \) is the wall thickness reduction at time \( t \), mm; and

\[ s_0 = s - C_1, \]

where \( s \) is the nominal tube wall thickness, mm; and \( C_1 \) is a supplement to the calculated wall thickness, mm.

In this case, the service life \( \tau \) of a heat-resistant metal based on the long-term strength condition can be determined with the aid of the known equation of damage accumulation [5], incorporating a coefficient representing the reserve of working life of the metal, \( \omega \):

\[ \omega = \frac{\tau}{\tau_f} \int_{0}^{\tau_f} \frac{dt}{[\sigma(t)]^m} \]

Here

\[ \omega = \frac{\tau_0}{\tau_f} \]

where \( \tau_0 \) is the calculated service life of the metal (without allowance for scale formation), usually equal to \( \tau_0 = 100,000 \text{ h} \), and \( \tau_f \) is the time to failure of the metal, h.

The integrand in (2) is the instantaneous rate of damage accumulation, and depends on the stress \( \sigma(t) \). It is usually expressed as a power function:

\[ \frac{1}{[\sigma(t)]^m} = B [\sigma(t)]^{-m} \]

(3)

where \( B \) is a coefficient depending on the temperature and the grade of steel; and \( m \) is a parameter depending only on the grade of steel.

Putting Eq. (1) into Eq. (3), we easily transform Eq. (2) to the form

\[ \omega = \frac{\tau}{\tau_f} \int_{0}^{\tau_f} \left[ 1 - \frac{\Delta s(t)}{s_0} \right]^{-m} dt. \]


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Scale formation occurs [3] both on the outer (gas) and inner (steam) sides, and therefore

\[ \Delta s(t) = \Delta s_1(t) + \Delta s_2(t), \]  

where \( \Delta s_1(t) \) is the thickness reduction on the gas side; and \( \Delta s_2(t) \) is that on the steam side.

To simplify the equations, the relative thickness reduction in (4) will be written in the form

\[ \frac{\Delta s(t)}{s_0} = 1.28 (G_1 t_0 + G_2 \eta(t)). \]  

Here

\[ G_1 = \frac{1}{s_0} \cdot 10^{a_1 - \frac{b_1}{T_1}}, \]  

\[ G_2 = \frac{1}{s_0} \cdot 10^{a_2 - \frac{b_2}{T_2}}, \]  

where \( a_1, b_1, c_1, \) and \( T_1 \) are the constants in the kinetic equation of corrosion [3] and the absolute temperature of the tube metal at the outer surface; and \( a_2, b_2, c_2, \) and \( T_2 \) are the corresponding quantities for the inner surface.

If we put Eq. (6) into Eq. (4), we get an integral which has not been tabulated and can be found only by numerical integration. Furthermore, in this case the integrand depends on a large number of parameters, and this complicates the application of the integration results. Thus the number of parameters must be reduced. For this purpose we can replace Eq. (6) by the structurally simpler expression

\[ \frac{\Delta s(t)}{s_0} = G t_0. \]  

Here

\[ G = 1.28 (G_1 + G_2 \eta(t)) \]

where \( \eta(t) \) is a coefficient.

For a fixed value of \( \tau \), \( \eta(t) \) is constant; therefore, substituting (9) into (4) and putting \( \omega \tau_f = \omega_0 \), we get

\[ \tau_0 = \int_0^\tau (1 - G t_0)^{-\omega_0} dt. \]  

Figure 1 plots the coefficient \( \eta \) vs. the service life \( \tau \) for three grades of steel; it was calculated by equating the integrals in Eqs. (4) and (10). From this figure we see that \( \eta \) depends little on \( \tau \), so that a rough value of \( \eta \) can be found at \( \tau_0 \); for more precise calculations we can use an iteration method.

In order to numerically evaluate the integral, it is more convenient to rewrite Eq. (10) as

\[ g \tau_0 = \int_0^g (1 - y t_0)^{-\omega_0} dy. \]  

Here \( y = gt \), where

\[ g = [1.28 (G_1 + G_2 \eta)] \frac{1}{t_0}. \]  

**TABLE 1**

<table>
<thead>
<tr>
<th>Type of heating surface</th>
<th>Steel</th>
<th>Wall thickness ( s_2, \text{mm} )</th>
<th>Temperature of outer surface ( T_1, \text{°K} )</th>
<th>Temperature of inner surface ( T_2, \text{°K} )</th>
<th>Calculated service life of metal ( \tau_{ref}, \text{h} )</th>
<th>Service life of metal with allowance for scale formation ( \tau_{ref}, \text{h} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convective superheater for live steam</td>
<td>12Kh1MF</td>
<td>6</td>
<td>813</td>
<td>804.3</td>
<td>100000</td>
<td>1497</td>
</tr>
<tr>
<td>Convective superheater for secondary steam</td>
<td>12Kh2MFSSR</td>
<td>4</td>
<td>857</td>
<td>856.5</td>
<td>100000</td>
<td>25641</td>
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<tr>
<td>Screen-type superheater</td>
<td>E1531</td>
<td>3.5</td>
<td>842</td>
<td>840</td>
<td>100000</td>
<td>53476</td>
</tr>
</tbody>
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